The QGP at RHIC

EMMI seminar:
Quark-Gluon Plasma and Cold Atoms
19-July-2010

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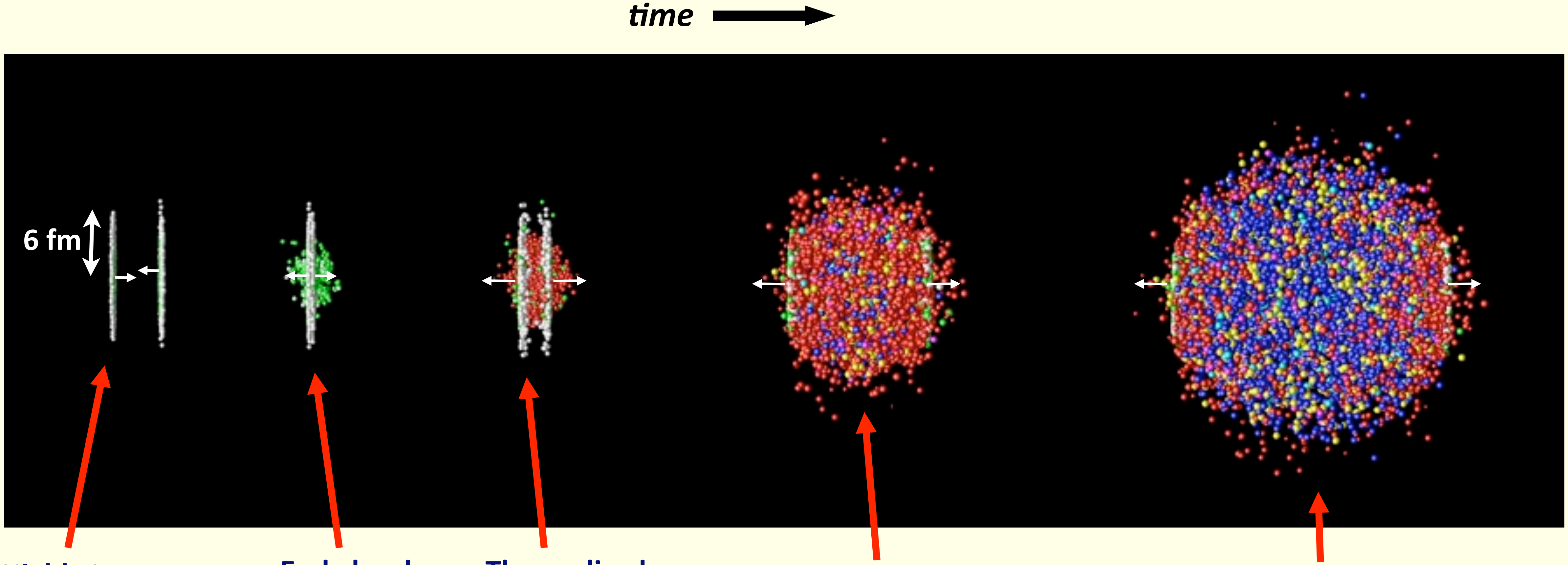
RHIC: Relativistic Heavy Ion Collider

- Operational since 2000
- Active experiments:
  - PHENIX
  - STAR
- Maximum energy in the nucleon-nucleon center-of-mass system
  - 200 GeV for Au+Au
  - 500 GeV for p+p
- Systems studied so far
  - p+p
  - d+Au
  - Cu+Cu, Au+Au

RHIC at Brookhaven National Laboratory, USA

Ultra-Relativistic Heavy-Ion Collision



Highly Lorentz-Contracted Nuclei (Lorentz γ ~ 100)

Early hard parton-parton scatterings ($Q^2 >> \Lambda^2_{QCD}$)

Thermalized medium (QGP!?) ($T_0 > T_c$, $T_c \approx 160$–190 MeV)

Transition QGP → hadron gas

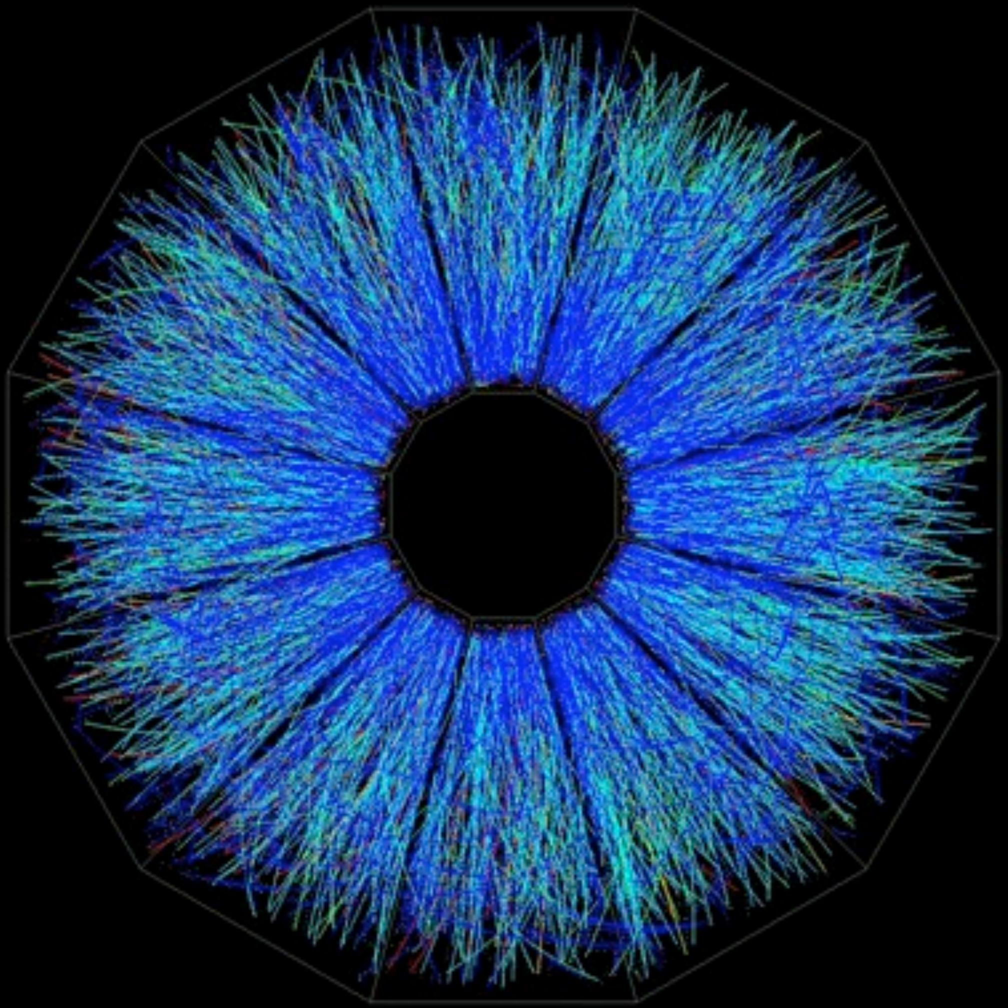
Freeze-out (after ~ 3 - 5 x 10^{-23} s)

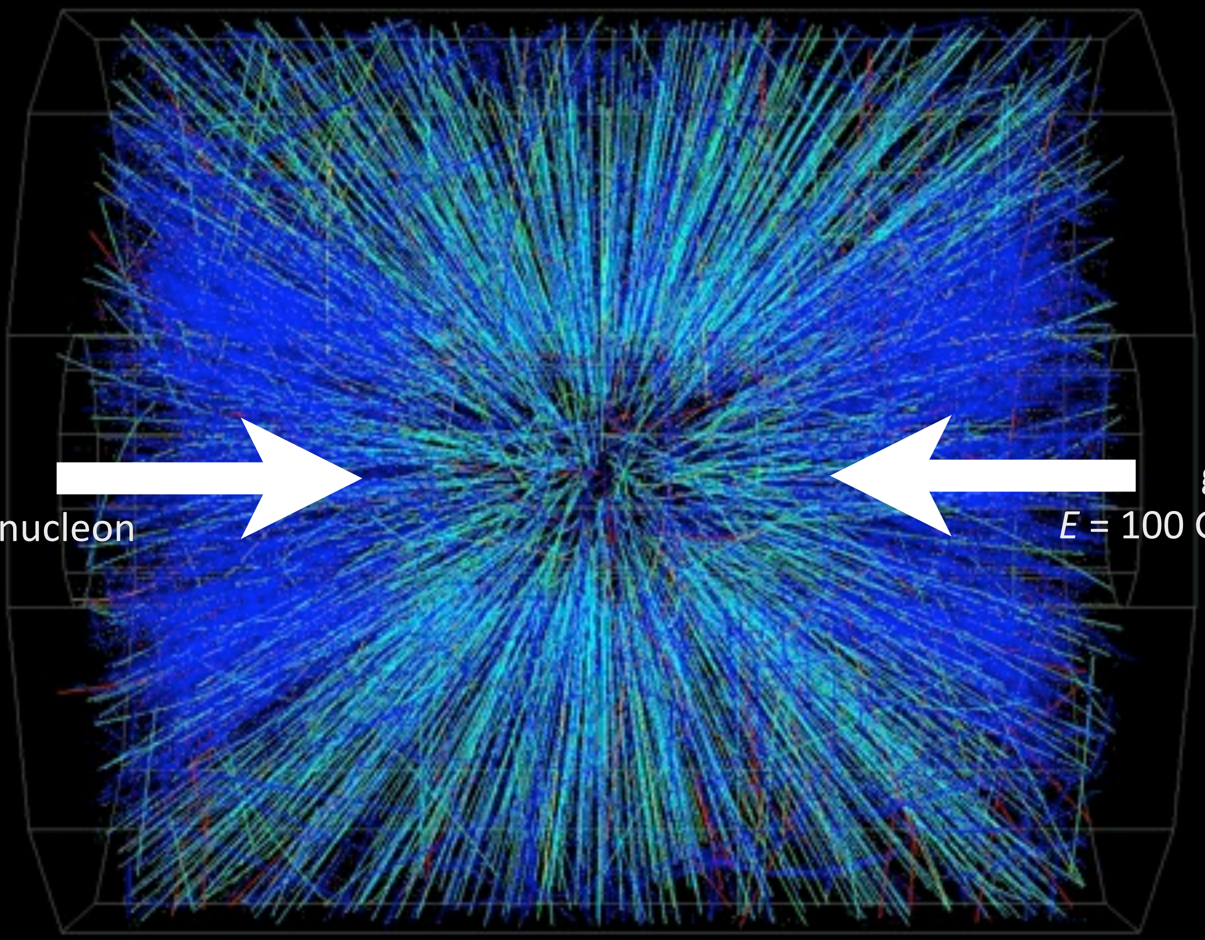
- Initial state is far from equilibrium
- Applicability of hydrodynamics is not clear *a priori*

Au+Au Collision at RHIC

About 7000 particles are produced per central Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV

Main observables:
spectra dN/d^3p of produced particles



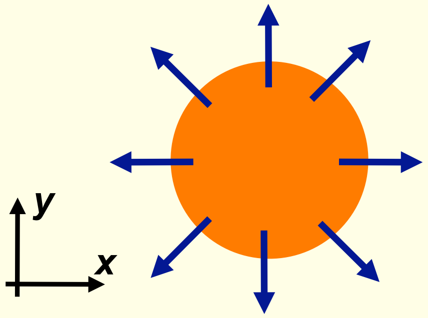


Evidence for Collective Behavior (I): Radial Flow

Plots from Ollitrault,
Eur. J.Phys. 29 (2008), 275

- For low momenta ($p_T < 2$ GeV/c) spectra roughly follow Boltzmann distributions with a characteristic temperature close to the QCD critical temperature
- In heavy-ion collisions the apparent temperatures for heavy particles are larger than for light particles
- Explanation: collective transverse expansion velocity v_T

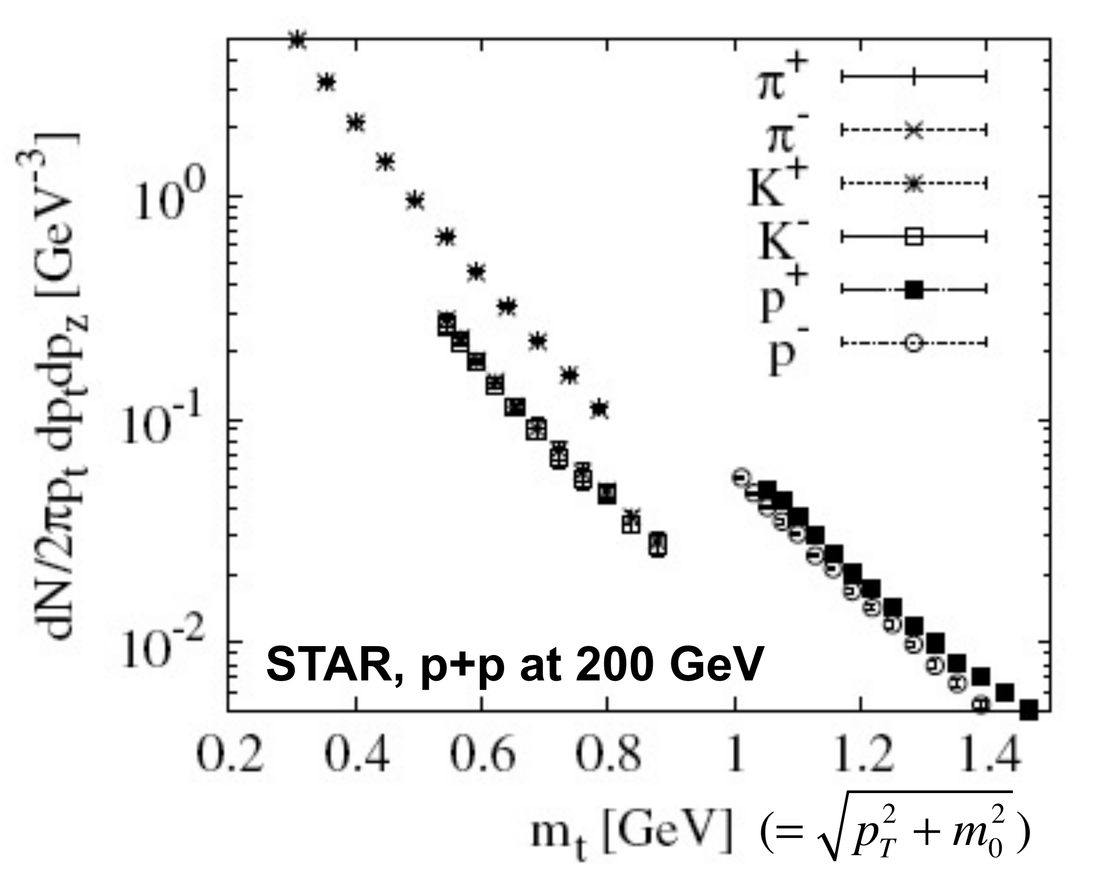
$$p_T^{\text{w/ boost}} \sim p_T^{\text{w/o boost}} + m v_T$$



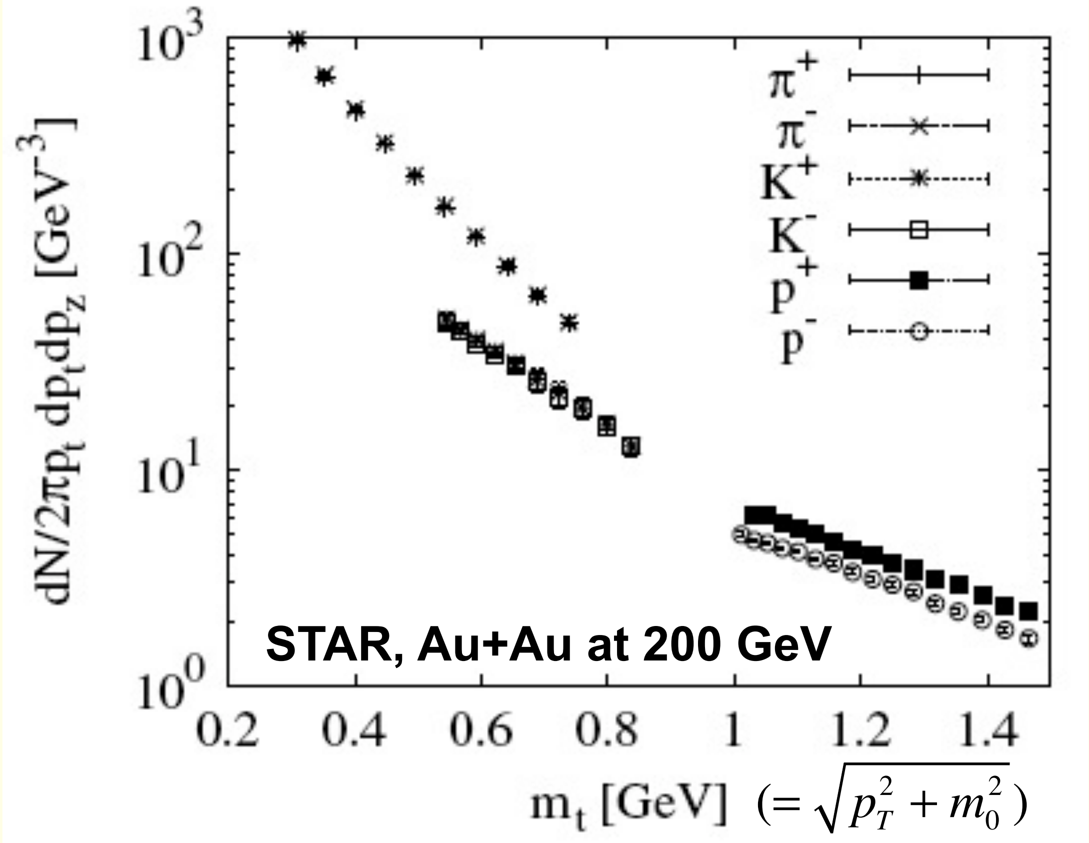
- Apparent (blue shifted) temperature

$$\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp\left(-\frac{m_T}{T_{\text{eff}}}\right), \quad T_{eff} \simeq T\sqrt{\frac{1+v_T}{1-v_T}}$$

- At RHIC v_T reaches $0.6 \cdot c$ at freezeout

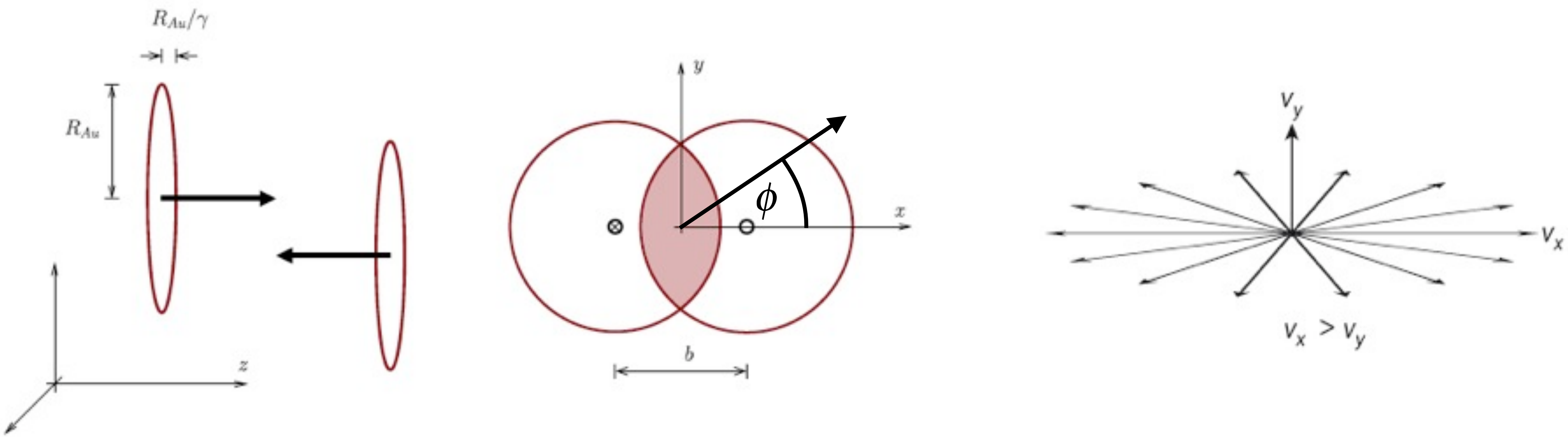


STAR, p+p at 200 GeV



STAR, Au+Au at 200 GeV

Evidence for Collective Behavior (II): Elliptic Flow

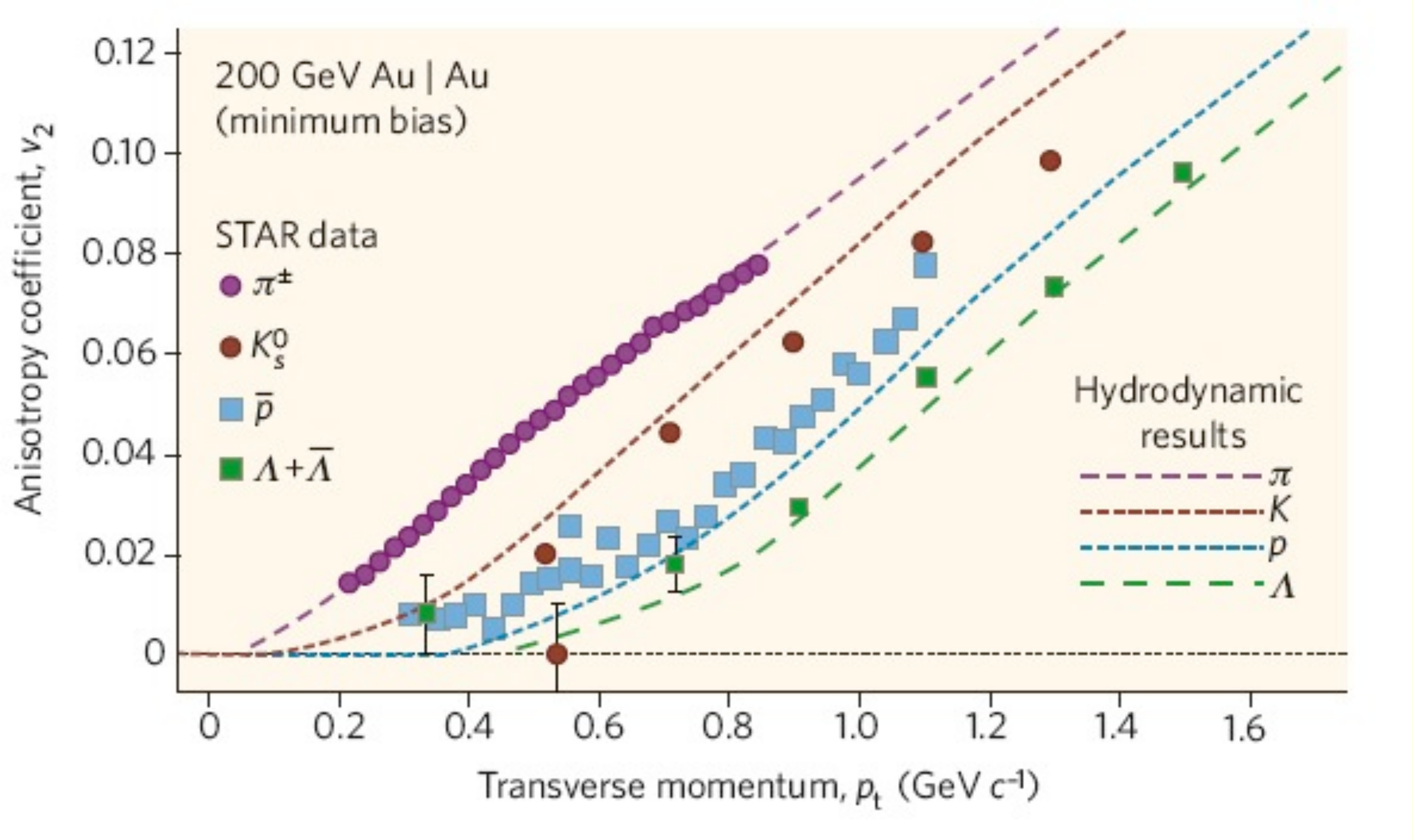


- Impact parameter vector and beam axis define the *reaction plane*
- Orientation of the reaction plane can be measured event-by-event
- Particle yields as a function of the angle ϕ w.r.t. the reaction plane:

$$E\left.\frac{dN}{d^3p}\right|_{p_z=0} = N_0(p_T)\cdot\left[1+2v_2(p_T)\cos(2\phi)+2v_4\cos(4\phi)+\ldots\right]$$

- For a typical mid-central collision at RHIC (b ≈ 6 fm): $v_2 \approx 6\%$
- Interpretation: Hydrodynamic evolution converts initial pressure gradients to velocity gradients in the final state

Elliptic Flow at RHIC



Plot from
Braun-Munzinger, Stachel,
Nature 448:302-309,2007

- Measured v_2 in good agreement with ideal hydro
- Hydro predicts mass ordering: $v_2 \sim \frac{1}{T}(p_T - v m_T), \quad v = \text{average transv. flow velocity}$
- Indeed observed!
- “Perfect liquid“ created at RHIC

Recap of Ideal Relativistic Hydrodynamics

- Energy/momentum density and flux in a fluid cell described by energy momentum tensor $T^{\mu\nu}$
- Ideal fluid: $T^{\mu\nu} = (\varepsilon + P) u^{\mu} u^{\nu} - g^{\mu\nu} P$
- Conservation of energy and momentum: $\partial_{\mu} T^{\mu\nu} = 0$
- Baryon current is conserved: $\partial_{\mu} j_B^{\mu} = 0 \text{ where } j_B^{\mu} = n_B u^{\mu},\ u^{\mu} = \text{4-velocity}$
- Conservation of energy, momentum, and baryon number give five independent equations for the six thermodynamic variables

$$\varepsilon(x), P(x), n_B(x), \vec{v}(x)$$

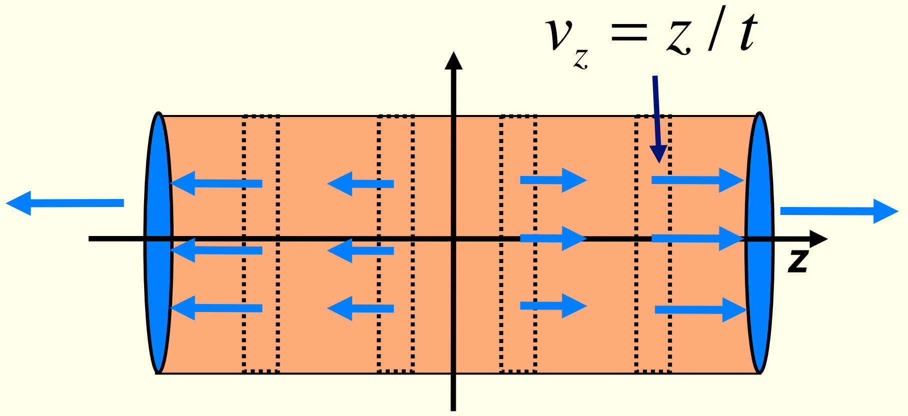
- Hence an equation of state is needed to close the system: $P(\varepsilon, \ldots)$

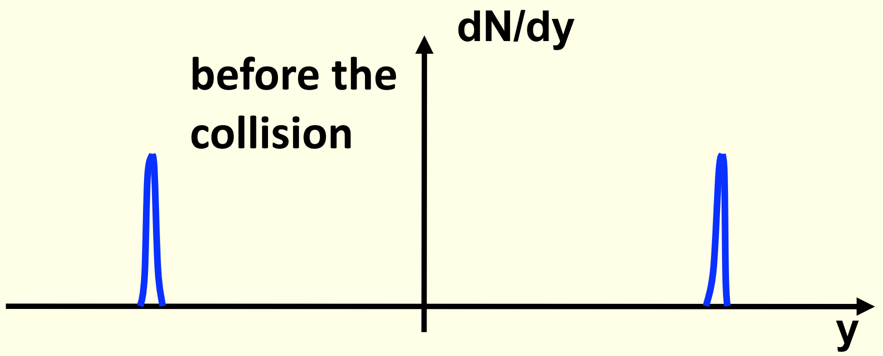
Bjorken Model (I)

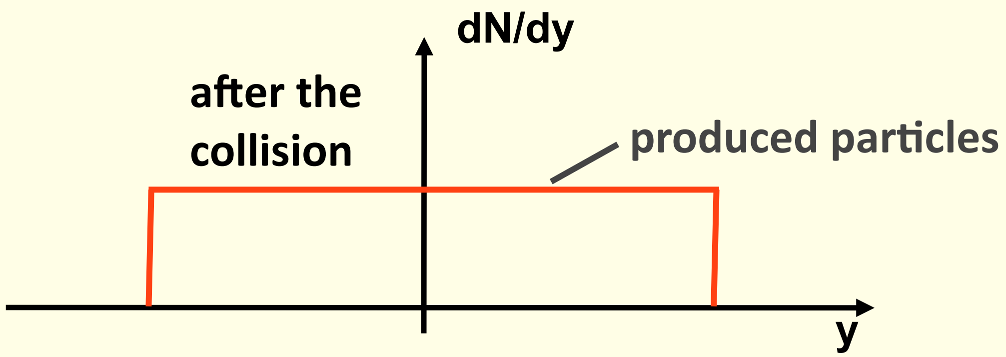
J.D. Bjorken, Phys. Rev. D27, 140 (1983)

- Bjorken provided a simple model for the space-time evolution of a heavy-ion collision
- Nuclei pass through each other and create a longitudinally expanding fireball
- The number of produced particles is independent of the rapidity *y*
- The evolution in proper time is the same for all comoving observers:

$$\varepsilon = \varepsilon(\tau), P = P(\tau), T = T(\tau)$$







$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \tanh^{-1}\beta_z, \quad \beta_z = p_z/E$$

Bjorken Model (II)

- Flow velocity profile in the Bjorken model („Hubble form“):

$$u_\mu = \gamma(1,0,0,v_z) = (t/\tau,0,0,z/\tau),\ \gamma = \text{boost factor},\ \tau = \sqrt{t^2 - z^2} = \text{proper time}$$

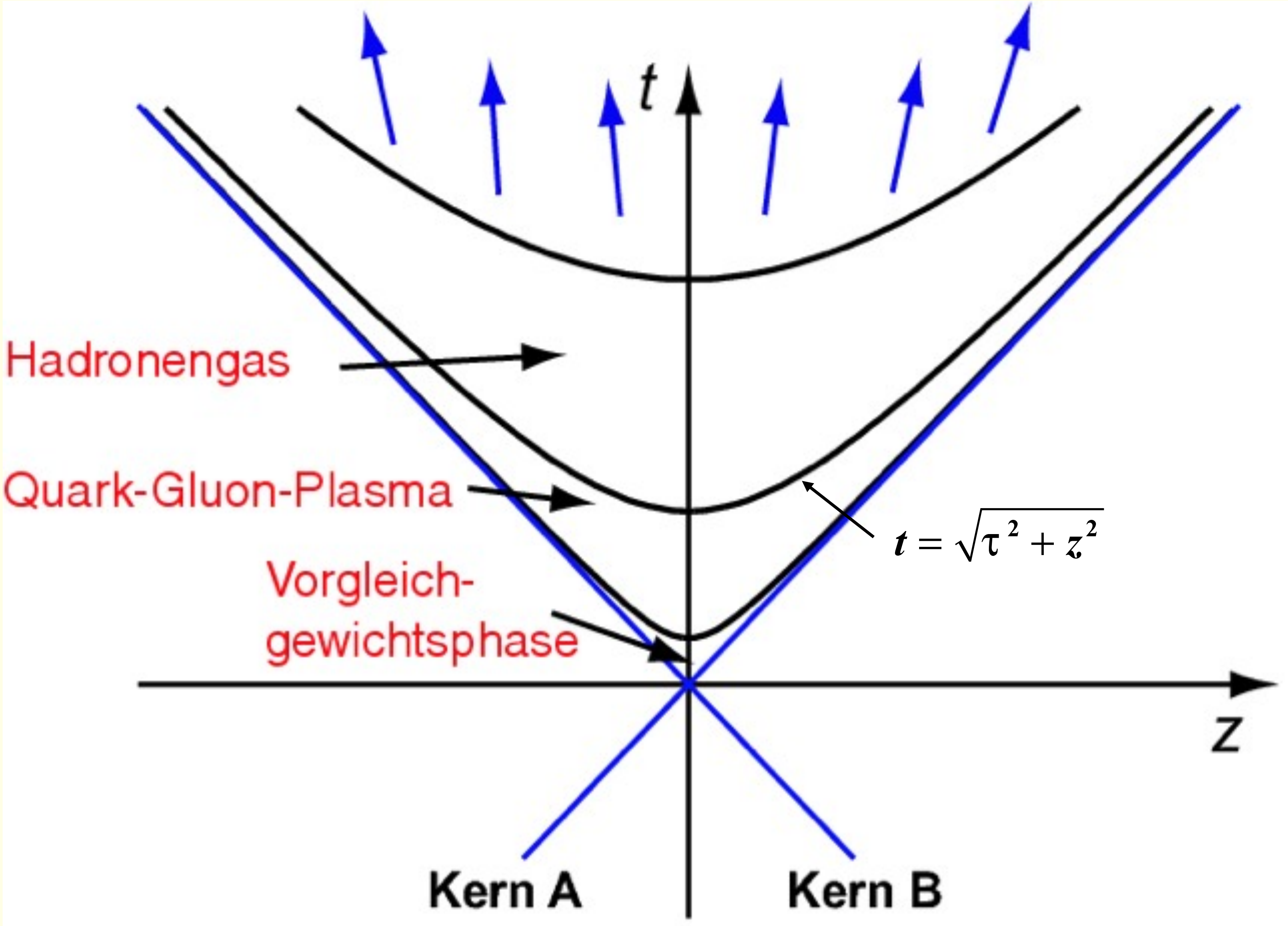
- This velocity field solves the relativistic Euler equation
- Entropy conservation leads to $\frac{d}{d\tau}\left[\tau s(\tau)\right] = 0$
- For an ideal relativistic gas $s \sim T^3$, $\varepsilon \sim T^4$ leads to

QGP lifetime

$$\varepsilon(\tau) = \varepsilon_0 \left(\frac{\tau}{\tau_0}\right)^{-4/3},\quad T(\tau) = T_0\left(\frac{\tau}{\tau_0}\right)^{-1/3},\quad \Delta\tau_{QGP} = \tau_0\left[\left(\frac{T_0}{T_c}\right)^3 - 1\right]$$

- Typical parameters at RHIC: $\tau_0 = (0.6 - 1.6)\,\text{fm}/c,\ T_0 = (300 - 425)\,\text{MeV}$
- Note that $T_0 > T_c \approx 160$ MeV: (Indirect) evidence for QGP formation
- The combination $\tau_0 T_0^3$ is constrained by the final multiplicity, but τ_0 and T_0 are not well constrained

Visualization of the Bjorken Space-Time Evolution



- Different phases separated by lines of constant proper time τ

Modeling of the Freeze-Out in Hydro Models

- Hydro models usually impose a sudden transition from a thermalized fluid to free-streaming particles
- Freeze-out typically happens on a hypersurface of constant temperature or energy density
- Distribution function *f* at the transition from hydro to kinetic theory parameterized by the local temperature *T* and flow velocity *u*

$$f(\boldsymbol{x},\boldsymbol{p},t) = \sum_i \frac{d_i}{\exp(p \cdot u / T) \pm 1}$$

- Observed particle spectra given by

$$\left(E \frac{dN}{d^3 p} \right)_i = \frac{1}{(2\pi)^3} \int d\Sigma_\mu p^\mu f_i(\boldsymbol{x},\boldsymbol{p},t)$$

Improvements of the Simple Bjorken Model (I): Transverse Expansion

- Transverse expansion becomes important at a proper time $\tau_0 \sim R / c_s$
- A very late times the expansion becomes three dimensional:

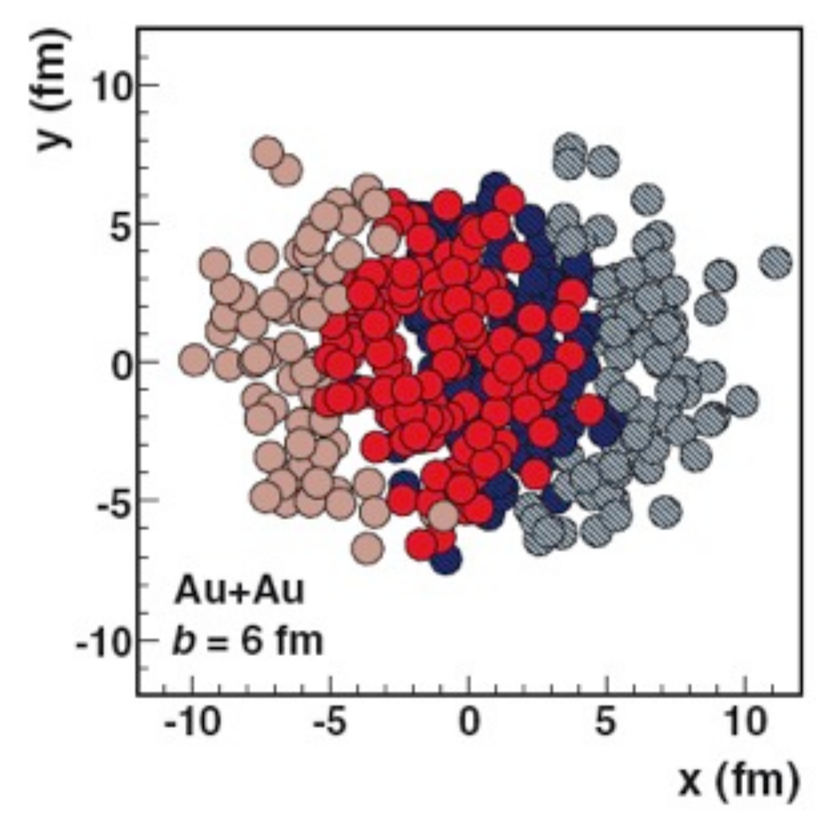
$$s(\tau) \sim \frac{1}{\tau^3}, \; T(\tau) \sim \frac{1}{\tau}$$

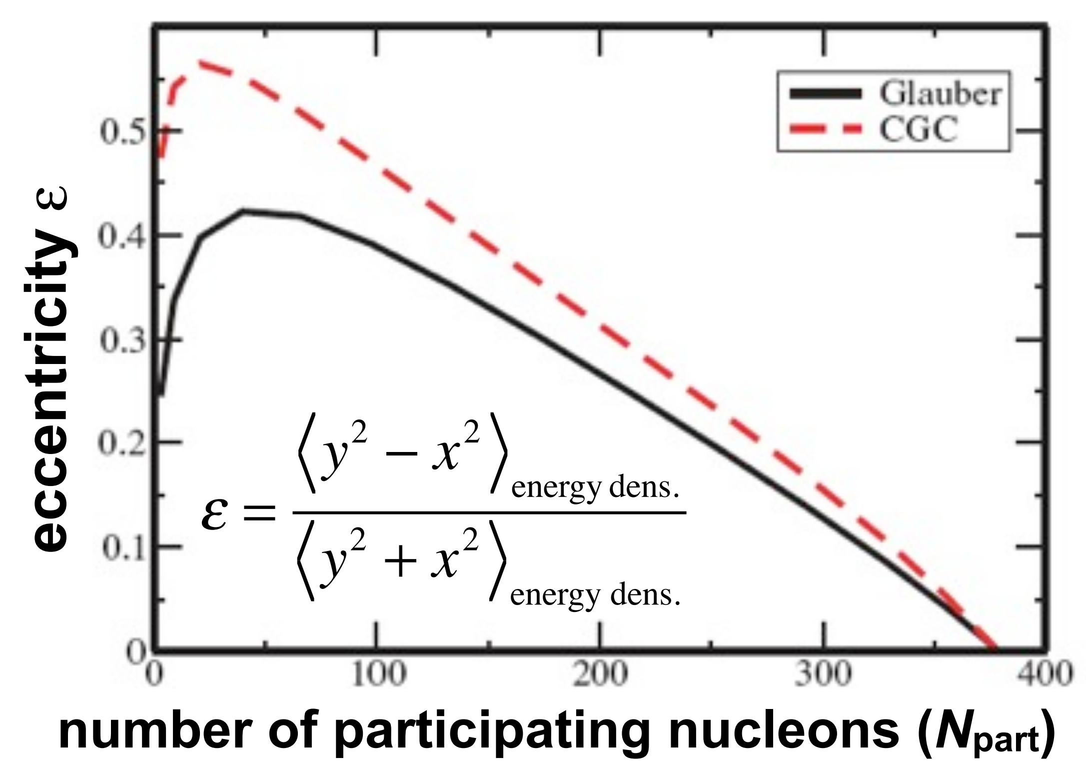
- Transverse expansion is caused by transverse pressure gradients
- Initial energy density (or entropy density) profile often taken from Glauber calculations:

$$s(x,y,b) \sim \frac{dN_{\text{part}}}{dx\,dy}$$

- Other models (e.g., the color glass condensate model [CGC]) predict different initial profiles

Example of a Glauber Monte Carlo event:





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle_{\text{energy dens.}}}{\langle y^2 + x^2 \rangle_{\text{energy dens.}}}$$

Improvements of the Simple Bjorken Model (II): Viscous Corrections

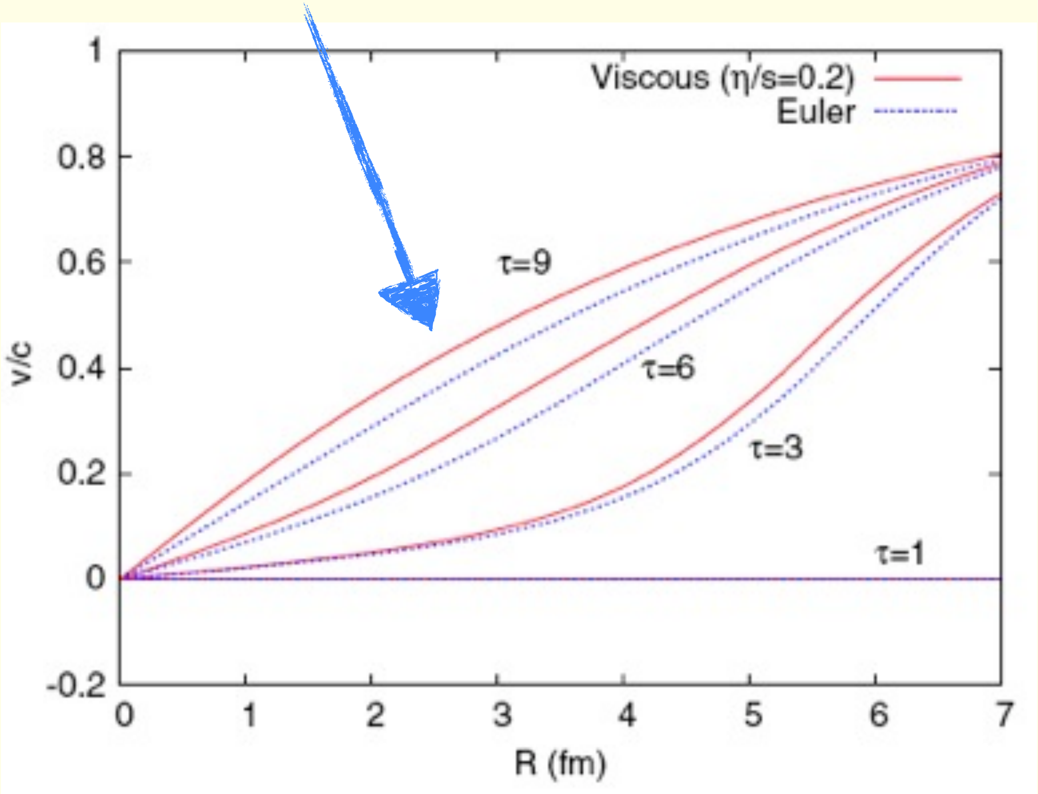
ideal hydro: $$T^{\mu\nu} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

with viscous corrections (for bulk viscosity ζ = 0): $$T^{\mu\nu} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & p + \frac{2}{3}\frac{\eta}{\tau} & 0 & 0 \\ 0 & 0 & p + \frac{2}{3}\frac{\eta}{\tau} & 0 \\ 0 & 0 & 0 & p - \frac{4}{3}\frac{\eta}{\tau} \end{pmatrix}$$

shear viscosity increases transverse pressure:

shear viscosity decreases longitudinal pressure:

Shear viscosity increases transverse flow velocities (however, effect on v_2 is small)

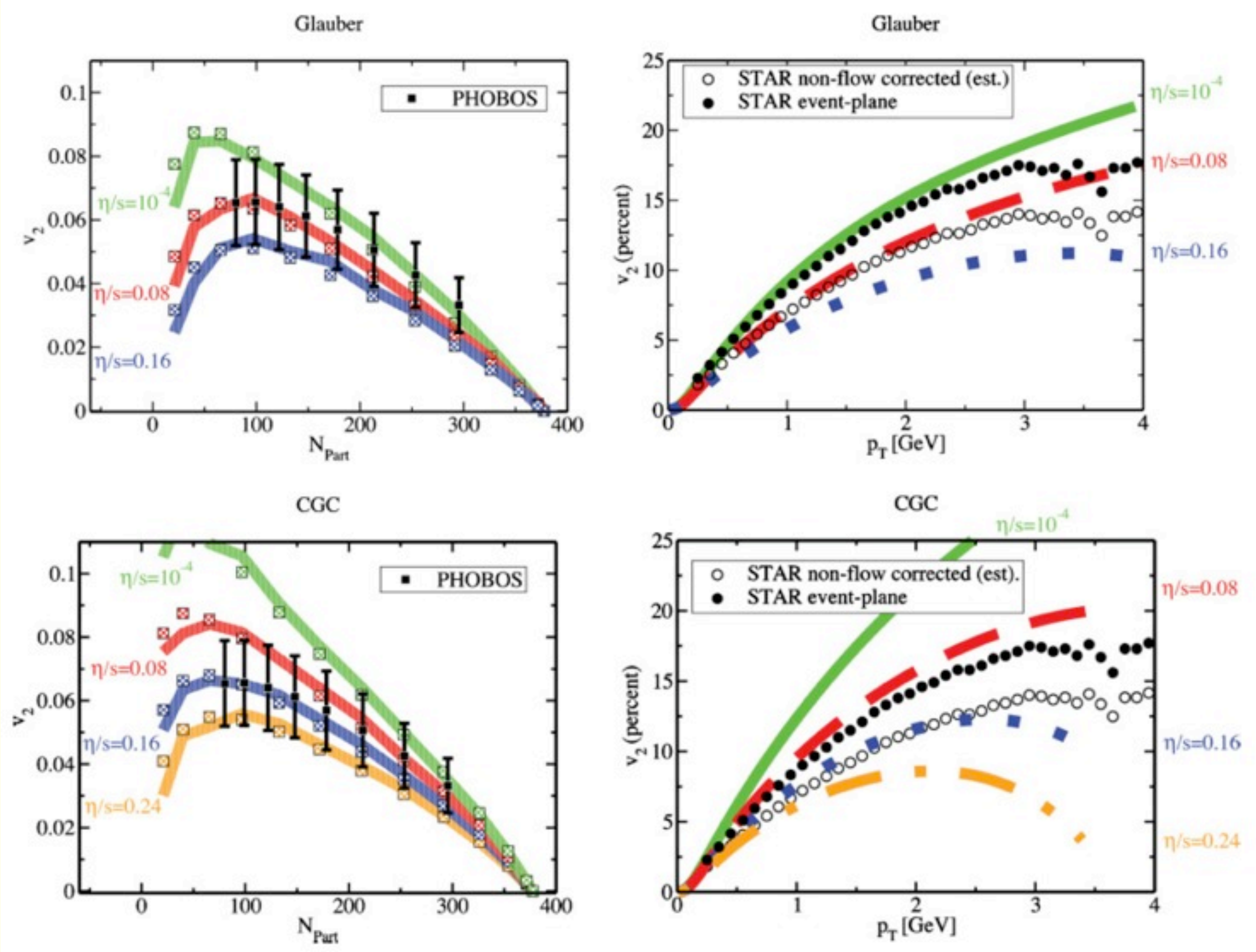


- Shear viscosity decreases longitudinal pressure and increases transverse flow
- This leads to a suppression of v_2
- In the model of Teaney and Dusling (discussed in the review) they find that viscous v_2 suppression is dominated by non-equilibrium corrections to the local thermal distribution function at freeze-out

Effects of Viscosity on Elliptic Flow (I)

- Viscous effects reduce v_2
- This opens the possibility to extract η/s of the QGP
  - Measure v_2
  - Compare to viscous hydro calculation
- However, the constraints on η/s are sensitive to the initial transverse profile of the energy density ($v_2 \propto$ initial eccentricity)
  - The Color glass condensate model produces higher transverse pressure gradients and thus allows for up to a factor 2 larger values of η/s
- Moreover, v_2 also sensitive to
  - variations of the EOS near T_c
  - bulk viscosity (often neglected)
  - late hadronic viscosity

Effects of Viscosity on Elliptic Flow (II)



Luzum, Romatschke,
Phys.Rev.C78:034915,2008

ecc. from Glauber:

$$\Rightarrow \quad 0 < \eta / s < 0.1$$

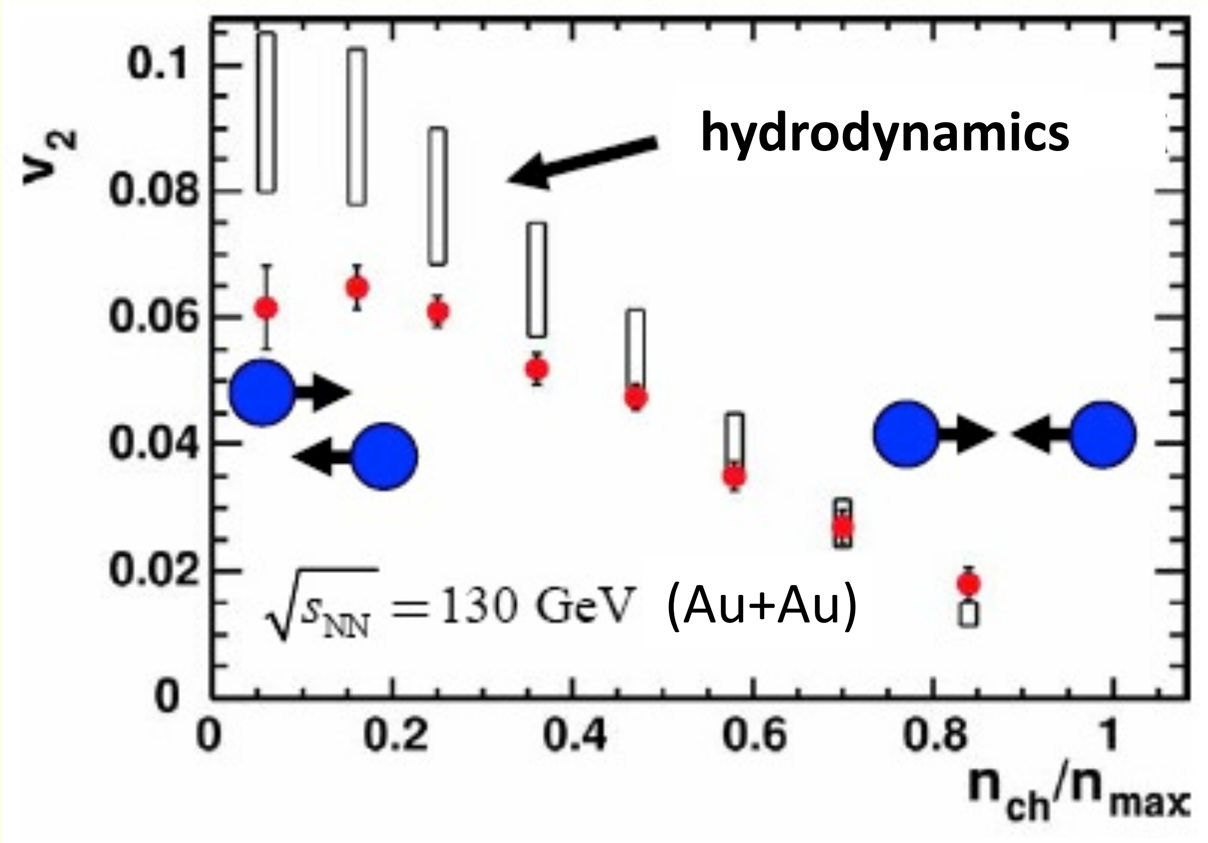
ecc. from CGC:

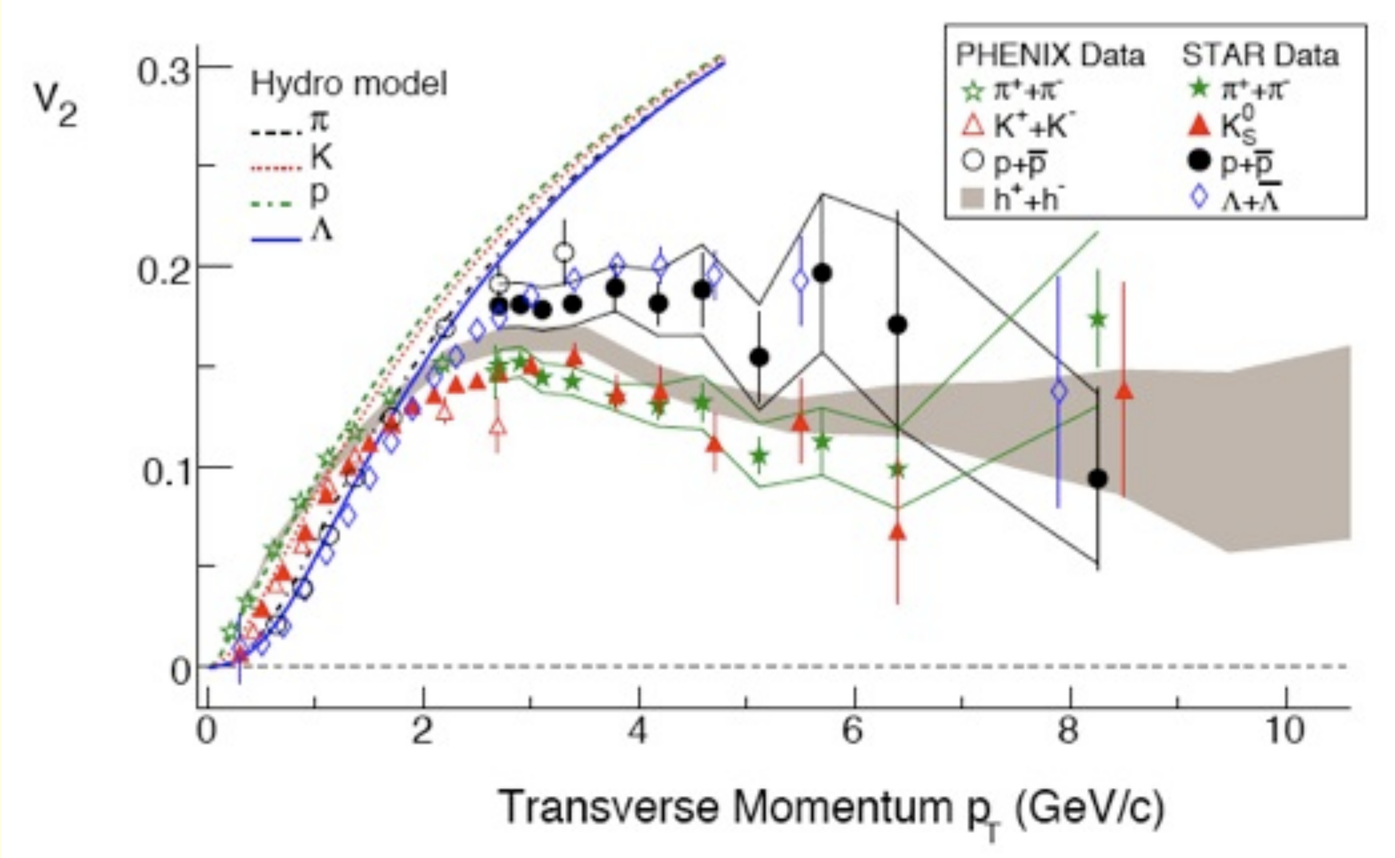
$$\Rightarrow \quad 0.08 < \eta / s < 0.2$$

conservative estimate for the QGP (taking into account e.g. effects of EOS variations, bulk viscosity, ...):

$$\boxed{\eta / s < 5 \times \left.\frac{\eta}{s}\right|_{\mathrm{KSS}} = 5 \times \frac{1}{4\pi}}$$

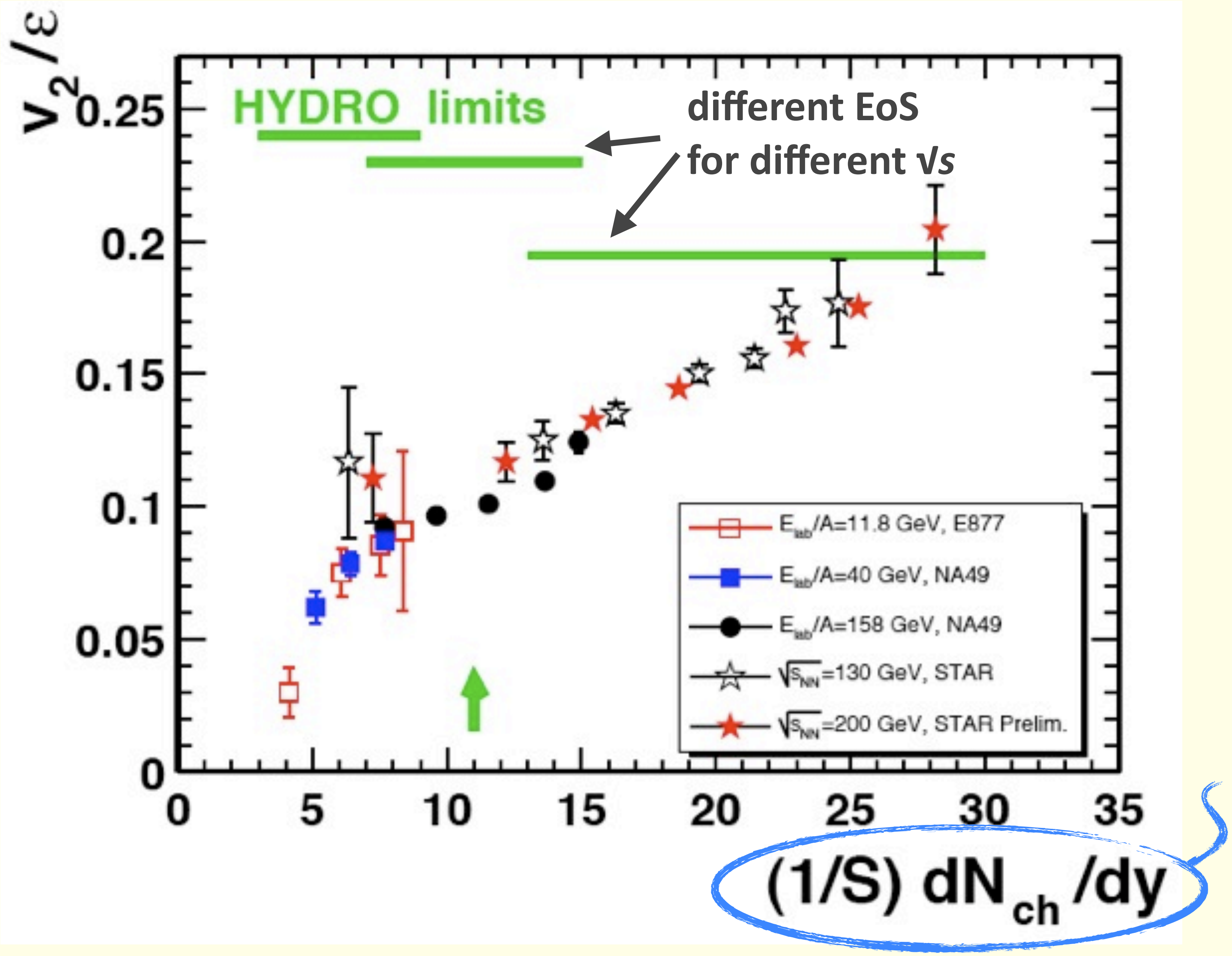
Three Interesting Facts about Elliptic Flow:
1. Breakdown of Ideal Hydro (I)





- Hydro description for Au+Au at RHIC only works in central collisions and for $p_T < 1.5$ GeV/c

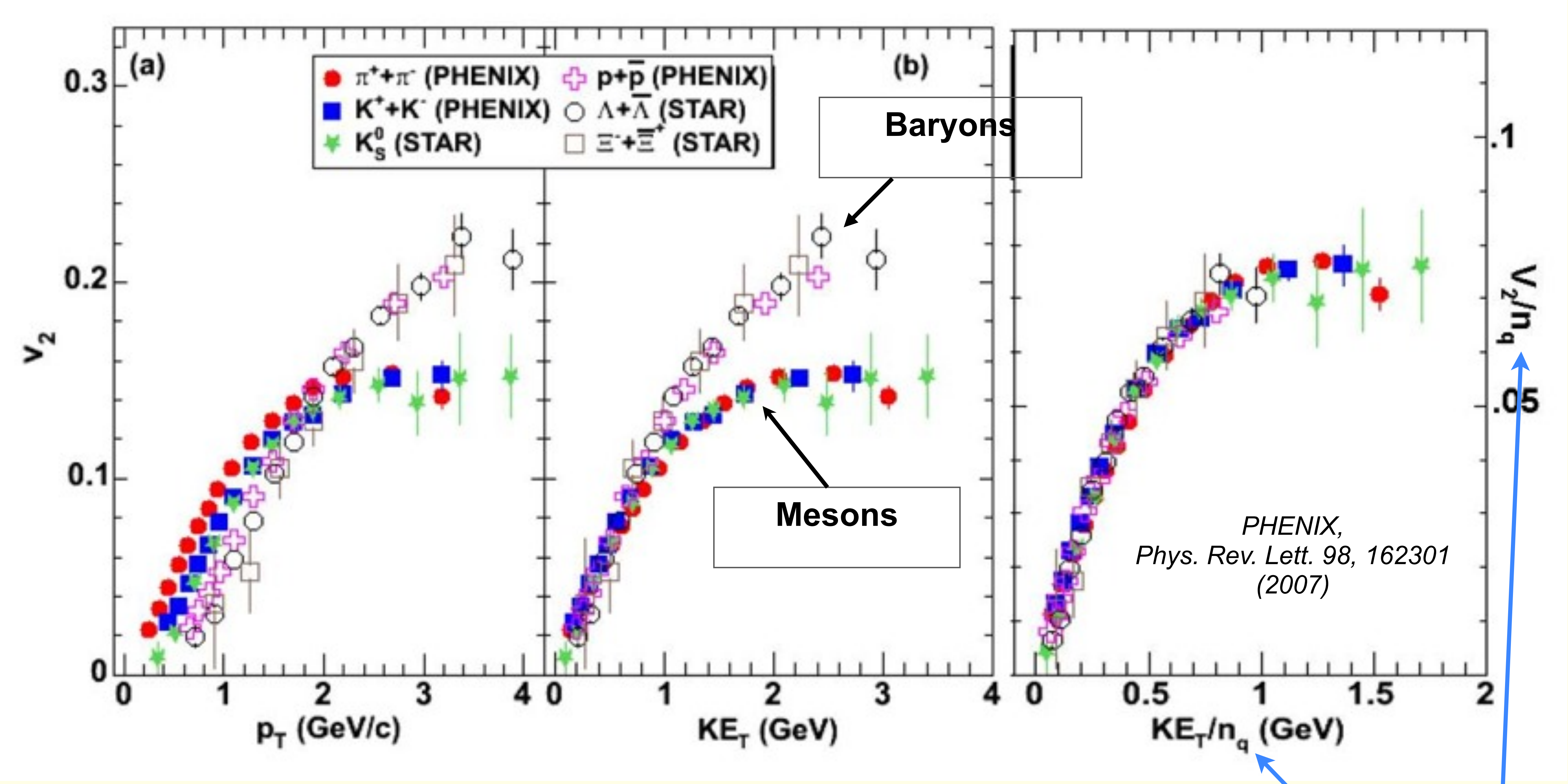
Three Interesting Facts about Elliptic Flow:
1. Breakdown of Ideal Hydro (II)



charged particle multiplicity per unit of rapidity per transverse area *S* of the source

- Hydro limit only reached at RHIC energies
- How will this plot look at LHC energies ?

Three Interesting Facts about Elliptic Flow:
2. Scaling with the Number of Constituent Quarks



PHENIX,
Phys. Rev. Lett. 98, 162301
(2007)

$\mathrm{KE}_T = \text{kin. energy in the transverse direction} = m_T - m_0$

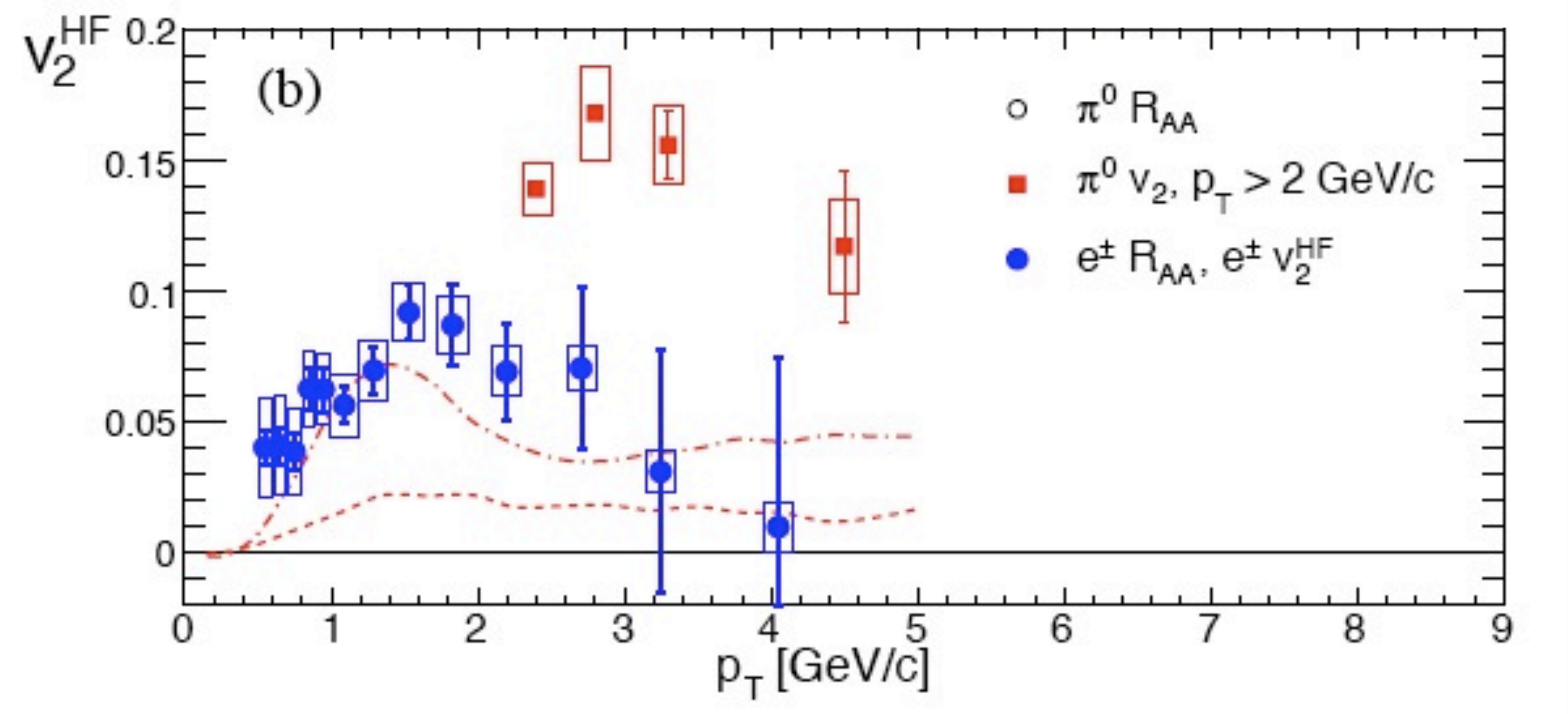
n_q=2 for mesons,
n_q=3 for baryons

- Scaling of v_2 with n_q suggests that the flowing medium at some point consists of constituent quarks
- Is there a transition from massless *u* and *d* quarks to constituent quarks ($m_u \approx m_d \approx 300$ MeV)?

Three Interesting Facts about Elliptic Flow:
3. Heavy Quarks Take Part in the Flow

measured

Example for a semi-leptonic heavy quark decay: $D^0(c\bar{u}) \rightarrow K^-(s\bar{u}) + e^+ + \nu_e$



- Current masses: $m_u \approx m_d \approx 4$ MeV, $m_c \approx 1270$ MeV, $m_b \approx 4200$ MeV
- Even though $m_{\text{heavy, quark}} > 200 \cdot m_{\text{light,quark}}$ heavy and light quarks exhibit a similar flow strength

Points to Take Home

- QGP at RHIC is close to an ideal fluid (close to KSS bound)
- Elliptic flow coefficient v_2 sensitive to viscosity of the QGP (viscosity reduces v_2)
- Largest systematic uncertainty in the extraction of η/s is the unknown initial eccentricity ($\varepsilon_{\mathrm{CGC}} > \varepsilon_{\mathrm{Glauber}}$)
- Current upper limit:

$$\eta / s < 5 \times \left.\frac{\eta}{s}\right|_{\mathrm{KSS}} = 5 \times \frac{1}{4\pi}$$

Useful References

- Thomas Schäfer, Derek Teaney, Nearly Perfect Fluidity: From Cold Atomic Gases to Hot Quark Gluon Plasmas, Rept.Prog.Phys.72:126001,2009
- Jean-Yves Ollitrault, Relativistic hydrodynamics for heavy-ion collisions, Eur.J.Phys. 29:275-302,2008
- Huichao Song, Ulrich W. Heinz, Extracting the QGP viscosity from RHIC data - A Status report from viscous hydrodynamics, J.Phys.G36:064033,2009
- Paul Sorensen, Elliptic Flow: A Study of Space-Momentum Correlations In Relativistic Nuclear Collisions, arXiv:0905.0174 [nucl-ex]